Influence of the domain structure of nano-oxide layers on the transport properties of specular spin valves

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Specular spin valves show enhanced giant magnetoresistive ratio when compared to other simpler, spin valve structures as a result of specular reflection in nano-oxide layers (NOLs) formed by the partial oxidation of the CoFe pinned and free layers. The oxides forming the NOL were recently shown to order antiferromagnetically below $T \sim 175$ K. Here we study the training effect in MnIr/CoFe/NOL/CoFe/Cu/CoFe/NOL specular spin valves at low temperatures (15 K). We observed that the training effect is related to the nano-oxide layer antiferromagnet ordering and to the evolution of the corresponding domain structure with the number of cycles performed. This allowed us to study the influence of the NOL domain structure on the magnetotransport of specular spin valves. © 2007 American Institute of Physics [DOI: 10.1063/1.2668422]

INTRODUCTION

When a ferromagnetic (FM) layer is adjacent to an antiferromagnet (AFM), the hysteresis loop of the FM is shifted from zero magnetic field ($H$) (Ref. 1) by an amount known as the exchange field ($H_{\text{exch}}$). Such effect is theoretically explained by considering the magnetization of the AFM layer divided in domains, giving rise to a net surface magnetization at the AFM/FM interface that controls $H_{\text{exch}}$.2–4

Another effect that sometimes arises in this system is the so-called training effect (TE), which is visible as the reduction of $H_{\text{exch}}$ with the number of hysteresis loops performed ($n$).3 The training effect is a consequence of the rearrangement of the (metastable) domain structure of the FM layer with each reversal of the FM,2 leading to a partial loss of its (AFM layer) net magnetization ($M$) and thus in a reduction of the exchange bias.5 The $H_{\text{exch}}(n)$ dependence usually follows (for $n > 1$):5

$$H_{\text{exch}}^n - H_{\text{exch}}^1 = \frac{\kappa}{n},$$

where $H_{\text{exch}}^n$ ($H_{\text{exch}}^1$) is the exchange field at the $n$th cycle (in the limit of an infinite number of cycles) and $\kappa$ is a system dependent constant.

Exchange bias is of extreme importance for present day magnetoresistive (MR) sensors in high density hard drives, such as spin valves (SVs) and tunnel junctions.6,7 A SV is constituted by two FM layers separated by a nonmagnetic metallic spacer.8 The magnetization of one of the FM layers (pinned layer) is fixed by an underlying AFM. That of the other FM layer (free layer) rotates when a small magnetic field is applied. To improve the magnetoresistance of such simple structure, one fabricates a nano-oxide layer (NOL) just above (in the middle) of the free (pinned) layer.6,9 We have recently shown that NOLs formed by CoFe oxides have a paramagnetic/antiferromagnetic transition at $T \sim 175$ K that strongly affects the MR properties of specular SVs.10,11 Such nano-oxide layers can, in fact, give rise to a significant exchange bias.12,13

In this work we present a study on the training effect in MnIr/CoFe/NOL/CoFe/Cu/CoFe/NOL specular spin valves, using MR($H$) measurements performed at $T = 15$ K. The training effect was never observed in common spin valves (without NOLs), indicating that the MnIr/CoFe interaction does not evolve with cycling. In the specular spin valve, TE was observed for $T < 175$ K and we thus relate it to the NOL-AFM ordering and to changes in the corresponding domain structure with $n$. Training effect in specular spin valves is characterized not only by the decrease of $H_{\text{exch}}$ with cycling but also by the decrease of the MR ratio. The influence of the NOL domain structure on the magnetotransport of specular spin valves was then studied, and we observed that FM spins coupled with domains in the AFM layer only very gradually align with the applied magnetic field for $H \gg 0$.

EXPERIMENTAL DETAILS

A specular spin valve structure was fabricated using a standard SV inserted between two NOLs of CoFe, as described in detail in Ref. 10. The NOL-SV with the structure Mn$_2$Ir$_{7}(90$ Å)/Co$_{90}$Fe$_{10}(14$ Å)/oxidation/Co$_{90}$Fe$_{10}(15$ Å)/Cu(22 Å)/Co$_{90}$Fe$_{10}(40$ Å)/oxidation/Ta(30 Å) was grown on a glass substrate using ion beam deposition, post-annealed in vacuum ($10^{-6}$ Torr) at 270 °C for 10 min, and then cooled in a 3 kOe applied field. The resulting exchange bias direction between the MnIr and (pinned) CoFe layers is here
taken as the positive direction. Temperature dependent transport measurements were performed in a closed cycle cryostat.\textsuperscript{14}

To study the training effect we performed field cooling runs (from 320 K) under a cooling field $H_0$ (applied along the MnIr/CoFe exchange bias direction). At least five consecutive magnetoresistance cycles MR were performed at $T=15$ K before the sample was heated again up to 320 K.

**EXPERIMENTAL RESULTS**

Magnetoresistance measurements in the specular spin valve at room temperature showed no training effect. However, with decreasing temperature, training effect appeared for $T=150$ K, just below the AFM ordering temperature of the oxides that constitute the nano-oxide layer.\textsuperscript{10} The observed training effect is thus related to changes in the AFM domain structure of the nano-oxide layer with field cycling. Furthermore, we did not observe any training effect in common spin valves (without NOLs), which indicates that the MnIr/CoFe exchange interaction remains unaltered with $n$.

Figure 1 depicts the first three MR($H$) cycles measured at $T=15$ K, after field cooling under $H_0=+7000$ Oe. For $n=1$, MR($H$) displays typical SV behavior: Low resistance ($R$) at positive fields, followed by a high $R$ state when the magnetization of the free layer reverses near zero field (antiparallel $\perp$ alignment), and finally a decrease to low $R$ at large negative fields (parallelism). However, an uncommon characteristic is also seen: MR only slowly goes to zero at $H\gg 0$, denoting incomplete $\parallel$ parallelism. This feature is related to the effects of the AFM-NOL domain structure on the magnetization of the pinned layer (see below).

The MR($H$) measurements evolve with $n$, showing a decrease in the pinned layer switching fields (particularly of the descending $H$ branch) and, consequently, of the exchange and pinned layer coercive fields (Fig. 1 and lower inset). Some of the AFM domains originally aligned along the cooling field ($\parallel$) change their $M$ direction and $H_{\text{exch}}$ decreases with cycling. This decrease is more pronounced from the first to the second MR($H$) cycle. Subsequent magnetoresistance cycles show much more attenuated differences. The training effect in our specular SV leads not only to the reduction of $H_{\text{exch}}$ but also to a lower GMR ratio due to a smaller antiparallelism between the magnetizations of the pinned and free layers at SV switching (near $H=0$; see also Fig. 1).

In the upper inset of Fig. 1 we observe that the residual magnetoresistance at large positive applied magnetic fields increases with increasing $n$. We attribute this effect to canted pinned layer FM spins (preventing full $\parallel$ parallelism for positive $H$, and thus $MR=0$) due to domains originating in the AFM NOL.\textsuperscript{15} With increasing $n$, the number of AFM domains in the negative ($\perp$) direction also increases. FM spins coupled with these domains will not align themselves with the applied positive magnetic field, resulting in the observed residual MR at $H\gg 0$.

Figure 2 shows the evolution of the exchange field for a large number of cycles (open circles). The corresponding MR($H$) curves were measured at $T=15$ K after zero field cooling. After 40 cycles the exchange field decreases to ~80% of its initial value. This reveals the importance of the contribution of the AFM-NOL to the overall exchange field (MnIr+NOL) at low temperatures. Fitting our data to the model described above shows an overall good agreement, indicating that $H_{\text{exch}}(n)$ follows Eq. (1), for $n>1$.

Field cooling runs (320–15 K) with different cooling fields showed that the SV-exchange bias strongly depends on $H_0$ (Fig. 3; $n=1$ points). Enhanced $H_{\text{exch}}$ results for $H_0=0$, since the pinned layer magnetization is, on cooling, aligned along the positive direction ($\parallel$). On the other hand, for $H_0=0$, the pinned layer is aligned in the opposite direction ($\perp$), leading to reduced $H_{\text{exch}}$.

The training effect also depends on the cooling field $H_0$, being smaller for $H_0=7000$ Oe than for positive cooling fields. Also, $H_{\text{exch}}$ extrapolates to the same value in the limit of large number of cycles for all $H_0=0$ ($H_{\text{exch}}^0$). On the other hand, different values of $H_{\text{exch}}^0$ are obtained for negative $H_0$. This indicates that the domain structure of the AFM-NOL has several stable configurations that depend on the magnetic history of the sample. For $H_0=0$, $H_{\text{exch}}$ tends to the same...
value, but for negative cooling field, the NOL domain structure evolves with \( n \) to a completely different configuration. The smaller TE observed for \( H_0 / H_1 \approx 270 \) indicates a more stable domain configuration of the field cooled state in this case.

**CONCLUSIONS**

We studied the training effect on specular spin valves, arising from the AFM nature of the oxides forming the NOL. The TE was related to variations in the NOL domain structure with \( n \) and its influence on the magneto-transport of specular spin valves was shown. FM spins strongly coupled to AFM domains in the negative direction do not align with the applied magnetic field, giving rise to a residual MR for \( H \gg 0 \).

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